Renewable and Sustainable Energy Reviews 33 (2014) 117–127

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Economic feasibility of utilizing forest biomass in district energy systems – A review

Shaghaygh Akhtari [a,1], Taraneh Sowlati [a,*], Ken Day [b,2]

[a] Industrial Engineering Research Group, Department of Wood Science, University of British Columbia, 2931-2424 Main Mall, Vancouver, British Columbia, Canada V6T 1Z4
[b] Alex Fraser Research Forest at The University of British Columbia, 2 South 7th Avenue, Williams Lake, Canada BC V2G 4N5

ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form
14 January 2014
Accepted 26 January 2014
Available online 22 February 2014

Keywords:
Techno-economic assessment
District energy systems
Forest biomass
Conversion technologies

ABSTRACT

Recent global protocols and agreements have motivated countries to use biomass for energy generation. However, the barriers in biomass utilization including variations in biomass availability, high moisture content, low bulk density and dispersed distribution of biomass have made investors reluctant to invest in bioenergy projects in some parts of the world. In this paper, in addition to a brief summary of the conversion technologies used for energy generation, a review of the world literature on techno-economic assessment of district energy systems using forest biomass as the primary fuel with references extending over two decades is provided. Although energy generation from forest biomass is found to be expensive in many countries, the review of literature revealed important factors that increased the share of biomass in energy production in other countries. These important factors include using more efficient technologies, providing governmental grants and subsidies, setting new policies in favor of biomass utilization, increasing emission reduction targets, and introducing tradable carbon credits. The feasibility of utilizing forest biomass in district heating systems has been examined in the literature mainly based on the costs, while considering social and environmental profiles of these systems could improve their acceptance. Future research studies on assessing the performance of biomass district energy systems should consider environmental and social impacts of these systems in addition to their costs.

Contents

1. Introduction

Energy consumption in residential and commercial buildings contributes to approximately one third of global greenhouse gas emissions ([1,2]); therefore, a decrease in the use of fossil fuels in these buildings could make a significant contribution in meeting emission reduction targets. One solution to reduce fossil fuel consumption in residential and commercial sectors is to decrease energy demand [3,4] by incorporating energy efficient solutions

* Corresponding author. Tel.: +1 604 822 6109.
E-mail addresses: akhtari.shaghayegh@gmail.com (S. Akhtari), taraneh.sowlati@ubc.ca (T. Sowlati), ken.day@ubc.ca (K. Day).
[1] Tel.: +1 604 827 4583.
[2] Tel.: +1 250 392 2207; fax: +1 250 398 5708.

http://dx.doi.org/10.1016/j.rser.2014.01.058
1364-0321

in the design of buildings such as thermal insulation, double and triple glazing, solar shadings, cavity wall, reflecting coating windows, etc. [5]. However, the energy efficient solutions on their own cannot offset the demand for energy in new buildings, and they are costly and time intensive when applied to existing buildings. Therefore, other strategies such as replacing fossil fuels with alternative renewable sources of energy [6] and improving energy conversion efficiency [7] should be applied along with decreasing energy demand to reduce fossil fuel consumption in buildings.

Several authors examined the economic feasibility of using renewable sources of energy for heating and cooling purposes. Esen et al. [8] evaluated the technical feasibility of using renewable biomass, solar, and ground energy and Chau et al. [9] studied the techno-economic viability of woody biomass boilers for heating greenhouses, respectively in Turkey and Canada. In [10], the ground source heat pump (GSHP) system was compared to conventional heating systems in Turkey. The results of this study indicated that GSHP showed economic advantages over conventional heating systems. In [11], two ground source heat pump systems, ground-coupled and air-coupled, were compared for space cooling. Ghafghazi et al. evaluated the energy sources including natural gas, wood pellets, sewer heat, and ground heat for district heating in British Columbia, Canada in [12] and ranked them in [13] using a multi-criteria approach.

District energy is an example of an efficient energy system in which thermal energy conversion takes place at a centralized plant and then a network of underground pipelines distributes the thermal energy to a group of users via hot water or low pressure steam [14]. District energy systems have higher efficiencies than individual energy systems as they minimize energy wastes [15]. In an investigation to choose the best energy system to heat detached homes in Sweden, Gustavsson et al. [16] showed that district heating was a more efficient and less expensive system with less environmental impacts than decentralized and electric heating systems. Difs et al. [17] also showed that converting to district heating in Swedish industries, where the electricity use is extensive, could result in significant reduction in the electricity and fossil fuels consumption. In a survey of literature, Rezaie et al. [18] have reviewed applications and classifications of district energy systems and discussed their technological, environmental, and economical advantages.

One important feature of district energy systems is their flexibility in using a wide variety of energy sources as their feedstock including conventional fossil fuels as well as renewables [19]. Using forest biomass, namely residues from logging activities, primary and secondary mill residues, urban wood wastes, and energy crops [20], in district energy systems provides the opportunity to produce heat and/or power with limited environmental impacts by utilizing renewable source of energy and increasing conversion efficiency simultaneously [19]. In comparison with other renewable sources, forest biomass can be stored for later use [21] and can be converted into solid, liquid, and gaseous fuels [22]. Using forest biomass in district energy systems creates jobs and promotes social and economic development in communities [23]. In comparison with other biomass resources, particularly agricultural biomass, forest biomass has higher bulk density [24] and because it is available throughout the year from various sources, it provides a more reliable feedstock and eliminates the long-term storage issue associated with agricultural residues [25].

Despite the environmental, social, and economic advantage of using forest biomass as fuel, forest biomass supplies are underutilized at the moment. Some barriers that restrict the use of forest biomass for producing energy are seasonal variations in biomass availability [26], limited availability and high production costs of biomass [27], existing technical limitations (e.g. conversion efficiency) and complex and costly fuel supply chain logistics [28], which is because of some physical characteristics of forest biomass. Low bulk density of biomass, which ranges from 50 to 130 kg m^{-3} depending on the biomass type [29], together with high moisture content, and low calorific value increase the logistical requirements of the supply chain including the size of handling system and storage space requirements [30]. Because of the issues discussed above, before investing in forest biomass for district energy, the availability of supplies should be investigated to assure a secure supply. The delivery cost of feedstock and conversion costs should be calculated not only to determine the cost structure but also to measure its competitiveness with alternative energy resources.

Many researchers have assessed the viability of bio-energy generation from forest biomass considering financial feasibility (e.g. [31]) and biomass availability (e.g. [32] and [33]). This paper is an overview of the previous studies that have been carried out to examine the feasibility of using forest biomass for generating heat and electricity in district energy plants and also in combined heat and power (CHP) systems. The purpose of this paper is to provide a review of the previous studies in the field of forest biomass based district energy by summarizing recent developments and highlighting factors that impact the economic viability of using forest biomass. The studies are categorized into three groups based on the indicators of feasibility: (1) studies on forest biomass supply availability, (2) studies focusing on delivered cost of biomass to the gate of district energy systems, and (3) studies that estimated the cost of energy generation from forest biomass, which includes at plant costs as well as the delivered cost of biomass. The reviewed literature in this paper indicates that heat and power production from forest biomass is relatively expensive. In order to increase the share of forest biomass in energy production and to benefit from its environmental advantages policy reforms may be required. Setting new policies and legalization and providing governmental subsidies will promote the economics of district energy from forest biomass.

2. Studies estimated forest biomass supply availability for utilization in district energy systems

Technical and economic viability of forest biomass district energy systems significantly depend on availability of forest biomass supplies since it quantifies the capacity of district energy system in terms of the size and number of plants. The spatial distribution of forest biomass supplies also determines the transportation distances and costs and therefore impacts the selection of the plant location [34]. Angelis-Dimakis et al. [35] have reviewed the literature on estimating biomass availability including forest biomass for energy purposes focusing on the tools and methods for estimating biomass supplies. Several studies have estimated forest biomass supply levels for bio-energy in general [36,37] and particularly for district heat and/or power generation [38,39] with the aid of geographic information system (GIS) and taking into account yield, forest area, and residue ratios.

Using thematic cartography information of soil and forest growth rates, Vasco et al. [38] quantified the annual forest biomass availability and the associated potential of electricity production at a regional level in Mozambique. Taking residue availability, protected forest areas, and transportation infrastructure into account, Vasco et al. [38] located combustion power plants. Viana et al. [39] evaluated the residue availability within the economic distance from a number of existing and in-construction plants in Portugal based on dendrometric data, biomass allometric regression equations (BARE), and biomass expansion factors (BEF). Allometric equations relate the total volume of above-ground biomass as well as various tree components (e.g. stem, top and branches) to

the diameter and height of a tree [40]. BEF is a multiplication factor that expands commercial round-wood harvest volume to account for non-merchantable components including tops and branches, and non-commercial trees [41]. Viana et al. [39] stated that estimated quantities would be sufficient to meet the demand of the plants if they produce combined heat and power. Otherwise, forest biomass should be co-fired.

To determine the feasibility of district energy from forest biomass based on supply availability, it is important to account for the factors that affect forest biomass production rates. For instance, forest residues production depends on forest management practices. Stand rehabilitation operations and salvage logging after natural disturbances, increasing harvesting levels to expand market, and thinning practices increase residue production [42]. The availability of mill residues depends on the quantity of the wood processed, wood properties, type of operation, and maintenance of the plant [35]. Also, it is important to make distinction between theoretical and real quantities of biomass. Several barriers limit the accessibility to the estimated, or in the other words, the theoretical quantities of forest biomass. In [39], the authors referred to technical restrictions (e.g. slope) which limit the collection process as a factor that should be taken into account to obtain real biomass quantities. Fisher et al. [43] addressed several barriers in estimating supply levels of energy crops: low cost of fossil energy sources, lack or small scale of operations and lack of established bio-energy markets, investments required and cost of land suitable for high yield production, lack of experience among farmers, deficiencies in information and technical support to farmers, and risk-aversion were non-technical barriers. Smeets et al. [44] named economic and ecological considerations as barriers that reduce forest biomass availability. Becker et al. [45] added social considerations to the aforementioned barriers and explained that factors such as payment offered to land owners to remove residues, concern for soil health, concern for energy independence, and the influence of consulting foresters impacted the owners' decision to harvest biomass.

3. Studies estimated the delivery cost of forest biomass to district energy plants

Once it has been guaranteed that enough forest biomass exists to operate a district energy system, the delivery cost of feedstock to the gate of district energy plants should be calculated. Forest biomass should be economically competitive with alternative sources of energy in terms of delivery cost. Forest biomass supply chain for heat and power production is complex and includes a series of activities that are required to transfer forest biomass from supplier locations to the heat and power stations. The necessary activities along the supply chain are: (1) in-field harvesting; (2) in-field handling and transportation of forest biomass to the road side, (3) storage which can take place at supplier location, at an intermediate facility, or at the plant location, (4) processing forest biomass into woodchips which can take place at any stage but preferably before transportation, (5) loading and unloading the transportation vehicle, and (6) transportation to energy plant [46].

Forest biomass delivery cost depends on the type of forest biomass, harvesting methods and tools, the configuration of supply chain amongst other factors. In [46–48], the delivery cost of different biomass types to energy conversion points were analyzed and compared. In these studies, bulk density was shown to have high impact in the choice of biomass type based on their delivery cost to district energy systems. Bulk density determines transportation and handling costs, which contribute to up to 50% of the total delivery cost [46]. Planning and managing the supply chain efficiently could significantly decrease the delivery costs of fuel feedstock to the facility [46].

For the same type of forest biomass, age and size of trees at the harvesting time impact the economics of forest biomass delivery to district energy plants. In [49], Ahtikoski et al. calculated the profit from selling energy woods to power plants in Finland and showed that the profitability significantly increased when trees with larger diameters were removed because cutting and forwarding costs decreased for larger trees. In [50], increasing the rotation period was found to enhance the profitability of harvesting whole trees for power production. When rotation period was increased, woodchips availability was increased and forest management cost was reduced.

The delivery cost of forest biomass to the plant is not only impacted by the physical characteristics but also by the configuration of the supply chain under which forest biomass is delivered to its destination. Forest biomass may be transported to the plants directly from the supplier locations. In the direct supply chain, residues are chipped at the roadside just before the transportation to the energy plant. Assuming an average annual quantity for forest biomass availability, Gautam et al. [51] calculated the annual total delivery cost of wildfire burnt pine trees to the gate of a 67 MW biomass CHP plant in Ontario, Canada. The supply chain in [51] consisted of felling, extraction, grinding, and transportation. Akhtari [52], however, argued that due to variations in availability of forest biomass over the year it would not be always feasible to transport forest fuel directly from supply sources to the energy plants. In some months of the year, particularly in winter when demand is high while sources are inaccessible due to severe weather conditions, supply shortage occurs. To balance the disparity between supply and demand amounts, storing forest biomass would be inevitable. In [52], the author analyzed the delivery cost of forest biomass feedstock for three configurations of supply chain: (1) direct flow, (2) flow via storage when chipping was carried out at supplier locations, and (3) flow via storage when chipping was done at the storage facility.

Within the supply chain, selection of machinery and equipment for forest biomass harvesting and transportation influences the total delivery cost [53,54]. In [53], Tahvanainen et al. developed a GIS-based model to simulate costs for wood energy supply chains to select the best transportation logistics for their supply chain. Their analysis showed that the choice between truck and railway transportation depended on the transportation distances. In [54], the most effective harvesting machinery was selected for harvesting whole trees. Their costing model allowed for selecting between chain saw and feller–buncher for felling trees and among swing yarder, cable skidder, and ropeway carrier for forwarding the felled trees. In their study, the interest rate on initial investment had a high impact on the profitability of harvesting whole trees. Introducing policies to overcome the problem of interest rate would turn it feasible to harvest whole trees for power production in Japan.

The choice of harvesting method, the form in which wood is transferred to the logging access roads, impacts the delivery cost of fuelwood since each method requires its own tools, equipment, and machinery. In [55], Mahmoudi et al. simulated the logistics of forest biomass supply chain using the full-tree to roadside method over a 1-year period of time, while Mobini et al. [56] incorporated three harvesting methods, (1) full-tree to roadside, (2) satellite harvesting, and (3) full-tree chipping, in the simulation model over the service life of the plant (20 years). In full-tree to roadside method, the felled trees are skidded to the roadside where they are processed into saw–logs. In this method, residues generated during operations together with trees not qualified as saw–log can be chipped at roadside. Using this method, costs of felling, skidding, and processing are not included in the delivery cost of woodchips to the energy plants. In satellite harvesting, after trees are felled and skidded to the roadside, they are transported to a satellite yard. At the yard, the trees are sorted into

Table 1
Summary of papers on economic assessment of forest biomass supply chain.

Author/ region	Objective	Conversion technology	Biomass feedstock	Method	Cost components
Allen et al. [46] **UK**	Compare the delivery cost of different biomass types to the plant	Power plant	Compared: • Forest residues • Short rotation forestry • Miscunthus • Straw	Per unit delivery cost (£ Odt^{-1}) Interest rate: not applicable Service life: not applicable	• Purchase • Harvesting, chipping/ bailing • Handling • Storing • Transportation
	Key findings: Since straw had a well-established supply chain and was a waste material that its growing cost was allocated to the crop produced, its delivery cost to the plant was the lowest among other biomass feedstock. On the other hand, miscunthus had the highest delivery cost mainly because of its high production costs. The authors suggested that increasing efficiencies of transportation and handling systems would decrease the delivery costs in future.				
Ćosić et al. [47] **Croatia**	Compare the delivery cost of different biomass types to the plants	Grate combustion (1 MWe and 10 MWe)	Compared: • Wheat straw • Corn stover • Forest residues	Levelized cost of electricity ($ MWh^{-1}): Interest rate: 18% Service life: 12 years	• Purchase • Transportation
	Key findings: In the 10 MW plant, forest residues provided the least expensive electricity followed by wheat straw and corn stover, respectively, while in the 1 MW plant, the cost of generating electricity was the lowest for wheat straw followed by corn stover and forest residues, respectively.				
Yoshioka et al. [48] **Japan**	Compare the delivery cost of different biomass types to the plant	Power plant (3 MW)	Compared: • Logging residues • Thinned trees • Broad leaved trees	Per unit delivery cost($ Mg^{-1}): Interest rate: not applicable Service life: not applicable	• Harvesting • Forwarding • Transportation
	Key findings: None of the biomass resources was economical to be used for power production. Logging residues though were less expensive than two other biomass resources. Advancement in harvesting and bundling technologies might reduce the delivery cost of feedstock to the plant.				
Ahtikoski et al. [49] **Finland**	Study the impact of thinning rates and size of trees on the profit from selling energy wood	Any power plant	Energy wood from young stands of pine	Profitability (revenue-costs) of thinning energy woods (€ ha^{-1}) Interest rate: not applicable Service life: not applicable	• Income from selling wood • Subsidies from government • In field transportation • Chipping • Long distance transportation
	Key findings: It was found out that profitability of thinning energy woods from young stands was associated with thinning rate and stem size of trees. Intensive thinning, in which a large number of trees are removed, improved the profitability of harvesting energy wood. Regardless of the thinning rate, when only trees with diameters larger than 3 cm were thinned, the profit from selling energy woods increased significantly because cutting and in-field transportation costs of larger trees were lower than those of smaller trees.				
Kinoshita et al.[50] **Japan**	Study the impact of rotation period on economics of whole trees for thermal energy	Any thermal power plant	Whole trees	Per unit delivery cost (JPY/m^{-3}) Interest rate: not applicable Service life: not applicable	• Felling • Bucking • Forwarding • Loading • Chipping • Transporting
	Key findings: Increasing the rotation period favored the economic profitability of supplying woodchips to existing coal thermal power plants in Japan. When rotation period was increased, there was an increase in the woodchips supply and a decrease in forest management costs.				
Gautam et al. [51] **Canada**	Calculate the delivery cost of forest biomass under the direct supply chain	CHP[a] plant (67 MW)	Wildfire burned tress	Per unit delivery cost ($ GMT^{-1}): Interest rate: 6% Service life: 5 years	• Felling • Collecting • Grinding • Transportation
	Key findings: The most and least expensive activities in the supply chain of biomass to the gate of plant were felling and grinding, respectively. The authors also emphasized on the considerable impact of transportation cost on the total delivery cost of feedstock when plant was located in a farther distance from the collection area than that in their case.				
Akhtari [52] **Canada**	Calculate the delivery cost of biomass for different configurations of supply chain	Direct combustion	Forest biomass: • Logging residues • Sawmill residues	Per unit delivery cost ($ Odt^{-1}): Interest rate: 6.5% Service life: not applicable	• Biomass • Loading • Chipping • Storage • Transportation
	Key findings: The variability in forest biomass availability determined the design of supply chain. Although chipping at supplier location and direct transportation of woodchips to the plant was the least expensive option, it was not always possible to transport woodchips directly to the plant. This was because the available biomass was not enough in some months of the year to meet the demand. Therefore, storing either chipped or non-chipped				

Table 1 (*continued*)

Author/region	Objective	Conversion technology	Biomass feedstock	Method	Cost components
	residues was essential. Between options with storage, chipping at supplier location and storing woodchips was less expensive than storing residues and chipping them at the plant.				
Tahvanainen et al.[53] **Finland**	To find the most economical transportation vehicle to deliver forest residue	CHP[a] plants	Forest residues	Per unit delivery cost (€ m^{-3}): Interest rate: not applicable Service life: not applicable	• Costs at roadside • Chipping/crushing • Loading and unloading • Transportation
	Key findings: The transportation distance determined the configuration of the supply chain. For short distances, the best supply chain option was to transport loose debris to the CHP plant and carrying chipping process at the plant. For medium distances, chipping residues at the roadside and truck transportation of woodchips to the plants offered the most economical option. Railway transportation of woodchips was cost-effective only for very long transportation distances.				
Kinoshita et al. [54] **Japan**	To find the most economical equipment for felling	Any thermal power plant	Whole trees	Selection of machinery to be used for low cost operations (JPY/m^{-3}) Interest rate: 3% Service life: 40 years	• Felling • Bucking • Forwarding • Loading • Chipping • Transporting
	Key findings: The authors found out that the amount of harvestable woody biomass was positively related to the harvesting costs of biomass. For their case study, the most profitable harvesting method was to perform felling using chainsaws or feller-bunchers and to use swing yarders for forwarding. The interest rate on initial investments had a significant impact on the profitability of woody biomass production.				
Mahmoudi et al. [55] **Canada**	To find the most economical harvesting system	Combustion 300 MW	Biomass from a mountain pine beetle-infested forest	Average per unit delivery ($ Odt^{-1}): Interest rate: 10% Service life: 1 year	• Felling • Skidding • Loading • Chipping • Transportation
	Key findings: Most of the time required to supply forest biomass from a conventional harvesting system to the power plant was taken by the logging contractors to fell, skid, and process trees and leave the residues at the roadside.				
Mobini et al. [56] **Canada**	To find the most economical harvesting system	Combustion 300 MW	Biomass from a mountain pine beetle-infested forest	Average per unit delivery cost ($ Odt^{-1}): Interest rate: 10% Service life: 20 years	• Felling • Skidding • Loading • Chipping • Transportation
	Key findings: This study considered the same case study in [49], extended the simulation model over the service life of plant instead of a one-year planning horizon and included satellite yard harvesting and full-tree chipping harvesting methods in the model. The results of the simulation model indicated that although the conventional harvesting method was the cheapest option, it was essential to incorporate two other harvesting systems because the availability of residues in the conventional system was limited.				

[a] CHP: combined heat and power.

saw–logs and fuelwood. Fuelwood trees are chipped at the yard. In this method, felling, skidding, and processing costs are shared between the energy plant and the logging company taking the residue to saw–log ratio into account. In full-tree chipping, the tree is completely considered as fuelwood and chipped at the roadside after is has been felled and skidded to the roadside. Both simulation models in [55,56] were used to estimate the logistics costs, carbon emissions and moisture content of delivered forest biomass to a power plant in British Columbia, Canada.

Table 1 summarizes the methods and key findings of papers reviewed on the economic assessment of forest biomass supply chain for district energy generation.

4. Studies estimated energy conversion costs from biomass

Although the delivery cost of forest biomass is an important indicator of its viability for district energy applications, at plant conversion costs should be calculated to determine the economic feasibility. At plant conversion costs, which include investment and operation and maintenance costs, may differ from those of alternative energy careers and this affects the feasibility of forest biomass utilization in district energy systems.

Converting the potential energy content of biomass into useful forms of energy is achievable through various technologies which are different in their efficiency, level of development, investment and operation and maintenance costs, and labor requirements. Three categories of technological conversion processes are thermochemical, biochemical, and chemical processes with variety of technology options within each group [57]. Fig. 1 illustrates various conversion processes and their products.

This study focuses only on thermo-chemical processes – combustion, gasification, and pyrolysis – since heat and electricity are main products of these processes and they are frequently used for generating district heat and electricity (to review conversion processes, the variety of technologies within each group, and their characteristics please refer to [58–64]). Chemical and bio-chemical technologies are used for alcohol production through fermentation and methane-enriched gas production through anaerobic digestion [57]. These liquid products are usually consumed in transportation sector and also in engines and turbine electrical power generators as fuel [65].

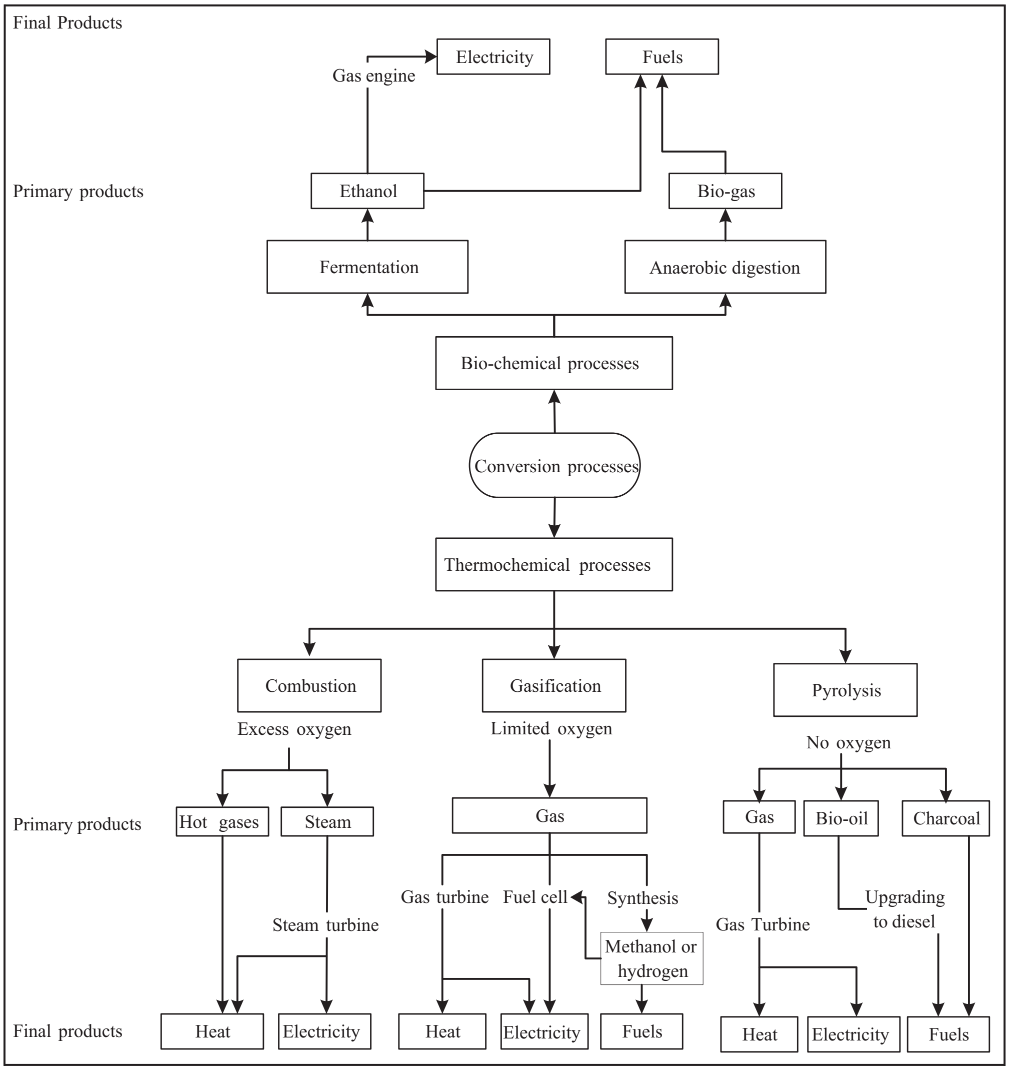


Fig. 1. Biomass conversion processes and their products.

The cost of energy conversion varies with the capacity of energy production, type of conversion technology, and type of feedstock.

A large district energy facility has a lower production cost compared to a small facility due to economy of scale. Schnieder et al. [66] and Fischer et al. [67] compared the cost of heat (in [66]) and electricity (in [67]) from forest biomass for different capacities of systems. The results of both studies indicated that the larger was the system, the less expensive was the cost of energy generation. The competitiveness of forest biomass with fossil fuels for district energy in both of the studies was conditioned to the governmental grants and subsidies along with taxes on CO_2 emissions in [66], and employing higher capacity factors[3] than current ones in [67]. One important consideration in regards to the system capacity is the trade-off between fuel cost and specific capital cost (capital cost per unit of produced energy). When the size of the system increases, system efficiency and specific capital cost increase as well. At the same time, larger systems require more forest biomass feedstock which increases forest biomass purchase cost and transportation cost.

The efficiency of the conversion technology is defined as the ratio of the useful output of the conversion technology, which can be heat or electricity, to its input in energy terms. Efficiency of forest biomass conversion technologies depends on physical characteristics of the fuel, and excessed air introduced to the conversion technology. Conversion efficiency is higher for the fuels with lower moisture content and higher heating value. To achieve complete combustion, excess air is introduced into forest biomass boilers; this excess air reduces the boiler efficiency [68].

Mitchell et al. [69], Caputo et al. [70] and Varela et al. [71] investigated the impact of conversion efficiency on the cost of electricity generation. These studies indicated that higher efficiencies do not guarantee lower electricity generation cost. The higher capital cost of more efficient technologies may overweigh the savings in the delivered cost of feedstock to the plant gate due to higher efficiency.

In [69], the cost of generating electricity was calculated using different conversion technologies: biomass integrated gasification combined cycle (BIGCC), pyrolysis, gasification, and combustion. Although the BIGCC and the pyrolysis systems were more efficient than the gasification alternative, the cost of generating electricity was the least in gasification. High capital cost of BIGCC and pyrolysis systems overweighed the cost savings, i.e., savings in material cost due to their high efficiencies. The combustion system was the least expensive system to acquire; however, its low efficiency resulted in higher biomass feedstock demand and consequently higher transportation cost than other options. Mitchell et al. [69] demonstrated that using feedstock with lower moisture content in pyrolysis required less drying, therefore,

[3] The capacity factor of a plant is the actual energy output of the plant over a given time period divided by the nominal capacity of the plant [83].

it reduced the cost of generating electricity from this technology. Caputo et al. [70] used net present value (NPV) to compare combustion and gasification systems. Although the gasification system was more efficient and had lower operating cost, at any production scale, the combustion system had higher NPV than the gasification system. This emphasized the higher impact of capital investment than that of operating costs in total economic performance of these systems. Positive NPVs were achieved for capacities larger than 25 MW for combustion system and larger than 30 MW for gasification system.

Feasibility of large scale (1 GWe) electricity production from short rotation crops in Spain was examined by Varela et al. [71]. Taking into account the minimum capacity of 15 MW for each power plant, a total of 28 power stations, 22 fluidized bed combustion (FBC) plants and 6 biomass integrated gasification combined cycle (BIGCC) plants, were considered for generating 1 GWe of electricity. Although BIGCC systems were more costly to acquire, they produced less expensive electricity.

Novel technologies, those in their early stage of life cycle, are characterized by high conversion efficiencies. However, the high capital and operating costs have restricted their use for energy generation. Contrary to novel technologies, well developed ones benefit from low capital and operating costs since they have been employed over a long period of time and were subjected to learning effects. Learning and gaining experience optimize the labor practice, increase automation, and increase the reliability of system [72]. Making decisions on the use of novel technologies without considering the learning effect might prolong the commercialization of these systems.

In [72], Bridgwater et al. compared the cost of forest biomass power generation cost using pyrolysis, gasification, and BIGCC novel technologies with that of combustion as an established technology considering a learning factor of 20% when 10 plant of each novel conversion technology were established. Their results showed that the difference between electricity generation costs among four conversion technologies is very small. When the authors ignored the learning factor, novel technologies produced much more expensive electricity than combustion system.

In addition to type of conversion technology, the economic viability of a district energy system is impacted by the physical characteristics of forest biomass feedstock. As it was discussed previously, moisture content and heating value of feedstock impact the conversion efficiency. Moreover, moisture content, bulk density, and distribution of forest biomass affect handling and processing costs which can contribute to a significant share of the total cost. The purchase price of feedstock is another determining factor in investigating economic feasibility of district energy from biomass.

Payback period and internal rate of return (IRR) of a small scaled (4-MM-BTUs-per-hour [1.17 MWh]) forest biomass district heating system were measured in [73] as indicators of economic performance of the system. Results revealed that low costs and moisture content of wood biomass and high alternative fuel costs had shorter payback period and higher IRR.

In several studies, the cost of district heat and/or power production was compared among various types of feedstock including forest biomass, agricultural biomass, and fossil fuels.

Broek et al. [74] and Gan et al. [75] drew comparisons among cost of electricity generation from forest residues, short rotation crops, and conventional fuels. In [74], Broek et al. evaluated the possibility of small scale electricity generation in a 100 kW combined heat and power (CHP) plant from forest biomass including forest residues, sawdust, and willow trees as short rotation crops in Ireland. The economic analysis in [74] revealed that electricity generation from willow plantations was not feasible unless forestry grants would cover some parts of their high production cost. The feasibility of using forest residues and sawmill wastes was subjected to co-firing them with coal or peat in existing power plants. Broek et al. [74] referred to price uncertainty as the major concern in using sawmill residues for electricity production in Ireland. Gan et al. [75] compared the cost of electricity generation from woody biomass including logging residues and poplar plantations with that of coal using a 100 MW biomass gasification combined cycle, a 400 MW pulverized coal system and a 428 MW integrated coal gasification combined cycle. Their economic analysis showed that electricity production from logging residues and poplar would be competitive with that from coal if either CO_2 emission taxes or emission reduction targets would increase. It is notable that in this study, poplar plantations to become competitive with coal required significantly tighter emission reduction targets and higher emission taxes than logging residues.

The economics of district energy from forest biomass with that from agricultural biomass was compared in [76,77]. Kumar et al. in [76] ranked straw from wheat and barley, harvesting residues, and whole forest trees for electricity production in Western Canada based on the levelized cost of electricity. Kumar et al.'s [76] evaluation indicated that whole forest trees were the least expensive option followed by straw and harvesting residues, respectively. In this ranking, yield per hectare was a determining factor. High transportation cost due to the very low yield of harvesting residue placed this source in the third place with a considerable difference with straw in the second position. Straw had a lower yield than whole forest trees, but good access to roads offsets a part of transportation cost, and thus the electricity cost from whole forest trees and straw were close. Kumar et al. [76] stated that electricity generation using biomass was not economical in Western Canada. Introducing greenhouse gas credit might turn biomass based electricity generation economical, though. Rodriguez et al. [77] evaluated the feasibility of electricity generation from agricultural residues (crop stubble) and forestry residues (harvesting and sawmill residues) by calculating the levelized cost of electricity generation. In their work, the cost of generating electricity from crop stubbles was much more expensive than forest residues. Low bulk density of crop stubble would result in high delivery cost of biomass to the plant. Although found to be expensive, Renewable Energy Certificates (RECs) in Australia have turned the biomass utilization into an economically viable option for small scaled electricity generation (less than 50 MW).

Dwivedi et al. [78] and Yagi et al. [79] compared district energy cost from various types of forest biomass. In [78], Dwivedi et al. compared eucalyptus hybrid, *Acacia nilotica*, and *Acacia tortilis* for electricity generation in India. The unit cost of electricity generation varied with respect to the energy plantation and was the least expensive for *A. nilotica* and the most expensive for *A. tortilis*. To determine the overall feasibility of using forest biomass for district electricity production, Dwivedi et al. [78] calculated the average net present value of electricity generation from these three types of energy plantations using gasification as the conversion technology. In this work, the average NPV was negative, even when a total saving of $25 t^{-1} was considered due to the elimination of carbon dioxide emissions. The authors argued that the investment in the 100 kW forest biomass gasifier would become feasible if the government would provide fiscal incentives to cover the costs of the gasification unit, civil works, and distribution network establishment. Sawmill wastes, logging and thinning residues were considered for generating heat and power in a small scaled gasification CHP plant in a study by Yagi et al. [79]. Considering the current stage of technology, sales price of electricity, and production cost of biomass fuel, only energy generation from sawmill wastes was feasible in this study. However, for lower prices of biomass production, logging residues might become feasible to be used if the gasification entered the commercialized stage. Thinning residues appeared not to be an economical source in this case because of high thinning cost.

Table 2
Summary of papers on techno-economic assessment of district energy generation from forest biomass.

Author/region	Objective	Conversion technology	Biomass feedstock	Method	Cost components
Schneider et al. [66] **Germany**	Compare the cost of electricity generation using different renewable sources over a range of capacities	Combustion systems: • 40 kW • 1000 kW • 2500 kW	• Thinning residues • Solar energy • Geothermal heat	Levelized cost of electricity (€ GJ^{-1}): Interest rate: 4% Service life: 15 years	• Investment • Feedstock production • Transportation • Operation and maintenance
	Key findings: Regardless of the system capacity, heat generation from fossil fuel was the least costly option. The heat from thinning residues was more expensive than that from other renewable energy sources. Heat generation cost decreased as capacity increased for all types of biomass feedstock. Taxes on CO_2 emissions from fossil fuels or subsidizing the investment cost would make woody biomass competitive with fossil fuels.				
Fischer et al. [67] **Vanuatu**	Compare cost of electricity generation using systems with different capacities	Gasification systems: • 10 kWe • 30 kWe	• Energy trees • Diesel	Levelized cost of electricity ($ kWh^{-1}): Interest rate:10% Service life: 20 years	• Investment • Fuel • Labor • Operation and maintenance
	Key findings: Higher capacity factors than current ones made electricity from forest biomass cost competitive with electricity from diesel. Regardless of fuel type, the 30 kW gasification system had always better economic performance than the 10 kW system.				
Mitchell et al. [68] **USA**	Compare cost of electricity generation using different conversion technologies and biomass types	20 MWe: • BIGCC[a] • Pyrolysis • Gasification • Combustion	• Logging residues • Short rotation coppice residues	Levelized cost of electricity ($ KWh^{-1}): Interest rate: 10% Inflation rate: 5% Service life: 20 years	• Investment • Feedstock delivery • Operation and maintenance
	Key findings: Gasification system generated the least expensive electricity. BIGCC and pyrolysis systems had higher conversion efficiencies and required less material to be bought than combustion system; however, their high investment cost made them uneconomical to be adopted. The conversion efficiency of the combustion system was so low that material cost overweighed the low capital cost.				
Caputo et al. [70] **Italy**	Compare the cost of electricity generation using different conversion technologies over a range of capacities	(5–50 MWe) • Combustion • Gasification	Forest biomass in general	Net present value (NPV) (€) Interest rate: 9% Service life: 20 years	• Investment • Operating • Logistics • Revenue from sale of energy
	Key findings: Regardless of the system capacity, generating electricity in the combustion system was always less expensive. Low operating cost of the gasification system could not offset its high capital cost. Regardless of the conversion technology, larger systems had a better NPV.				
Varela et al. [71] **Spain**	Compare the cost of electricity generation using different conversion technologies	• FBC[b] (22 plants) • BIGCC[a] (6 plants)	Poplar trees	Levelized cost of electricity (€ GJ^{-1}): Interest rate: 5% Service life: 30 years	• Investment • Feedstock delivery • Land • Operation and maintenance
	Key findings: The BIGCC system demonstrated cost advantage over the FBC system. Considering all the plants, the fuel cost had the highest share in the average electricity price followed by investment cost and operation and maintenance cost.				
Bridgwater et al. [72] **UK**	Compare the cost of electricity generation using new and well-developed technologies	• Novel technologies • Commercialized technologies	Forest residues	Levelized cost of electricity (€ kWh^{-1}): Interest rate: 10% Service life: 20 years	• Investment • Feedstock delivery • Operation and maintenance • Utility costs • Overhead
	Key findings: Without considering the reduction in cost of electricity generation using novel technologies due to learning effects, commercialized technologies generated much less expensive electricity than novel systems. When the impact of learning effects on the costs was considered in the analysis, there was negligible difference between costs of electricity generation 17 using novel and commercialized technologies.				
Nicholls et al. [73] **USA**	To study the impact of fuel characteristics on the economics of district heat generation from forest biomass	Combustion(4-MMBTU h^{-1}) [d]	• Mountain pine beetled wood • Sawmill wastes	• Internal rate of return • Payback period Interest rate: 7% Inflation rate: 4% for first 10 years, 7% for the second 10 years Service life: 20 years	• Investment • Feedstock delivery • Operation and maintenance
	Key findings: Low wood fuel prices, low moisture content, and high alternative fuel cost were resulted in shorter payback period and greater rate of return. Fuel cost had the largest impact on the profitability of the project.				

Table 2 (*continued*)

Author/region	Objective	Conversion technology	Biomass feedstock	Method	Cost components
Broek et al. [74] **Ireland**	To compare the cost of electricity generation using different biomass types	CHP[c] (100 kW)	• Forest residues • Sawmill wastes	Levelized cost of electricity (€ GJ^{-1}): Interest rate: 5% Service life: 25 years	• Investment • Fuel cost • Operation and maintenance
	Key findings: Small scaled electricity generation in the CHP system was more expensive than the current sale price of electricity. Co-firing of biomass with peat or coal in existing electricity plants would result in considerable cost reductions in electricity generation.				
Gan et al. [75] **USA**	To compare the cost of electricity generation using different forest biomass types	• Pulverized coal (400 MWe) • Coal IGCC[a] (428 MWe) • Biomass IGCC[a] (100 MWe)	• Poplar trees • Logging residues	Levelized cost of electricity (€ GJ^{-1}): Interest rate: 6.5% Service life: 20 years	• Investment • Feedstock delivery • Operation and maintenance
	Key findings: Electricity generation in biomass IGCC system cost approximately twice as high as electricity generation cost in coal systems. Imposing tax on CO_2 emissions would increase biomass utilization for electricity production.				
Kumar et al. [76] **Canada**	To compare the cost of electricity generation using different biomass types	Combustion	• Straw • harvesting residues • whole trees	Levelized cost of electricity ($ MWh^{-1}): Interest rate: 10% Service life: 30 years	• Investment • Biomass • Transportation • Operating
	Key findings: None of the biomass sources generated electricity economically. Though, the least expensive biomass source to generate energy from was whole forest trees, followed by straw and harvesting residues. Biomass yield per hectare was a determining factor in this ranking. Introducing greenhouse gas credits might turn biomass based power generation economical.				
Rodriguez et al. [77] **Australia**	To compare the cost of electricity generation using different biomass types	Direct combustion (5 MW)	• Crop stubbles • Harvesting and sawmill residues	Levelized cost of electricity ($ kWh^{-1}): Interest rate:7.5% Service life: 30 years	• Investment • Fuel • Operation and maintenance
	Key findings: In general, electricity from forest residues was less expensive than that from agricultural residues. Electricity from both biomass sources was more expensive than that from coal. However, renewable energy certificates in Australia had turned it feasible to generate energy from biomass.				
Dwivedi et al. [78] **India**	To compare the cost of electricity generation using different types of energy plantations	Gasification (100 kW)	Energy plantations	Net present value (NPV) ($) Interest rate: 8% Service life: 15 years	• Investment • Fuel • Transportation cost • Operating • Transmission and distribution
	Key findings: NPV was always negative even when carbon credits were included in the economic analysis. In order to make it feasible, subsidies from government to cover capital costs were essential.				
Yagi et al. [79] **Japan**	To compare the cost of electricity generation using different forest biomass types	CHP[3] (< 300 kWe)	• Sawmill • Logging • Thinning residues	Levelized cost of electricity ($ kWh^{-1}): Interest rate: not discussed Service life: not discussed	• Fuel • Investment • Transportation • Operation and maintenance
	Key findings: Electricity generation from sawmill residues was already economical. Logging residue utilization for electricity generation would become feasible if biomass price would reduce and the investment cost of gasification would decrease. Thinning residues were never economical to use because of high thinning cost.				

[a] BIGCC: biomass integrated gasification combined cycle, IGCC: integrated gasification combined cycle.
[b] FBC: fluidized bed combustion.
[c] CHP: combined heat and power.
[d] MM-BTUs: one million British thermal unit (BTU).

Table 2 summarizes the papers reviewed on economic assessment of using forest biomass for energy generation in district heating systems.

5. Discussion

Reviewing previous literature revealed some common findings. The most important parameters that can affect the economic feasibility of investing in forest biomass district energy systems are summarized below.

Biomass feedstock can impact the economic performance of a district energy system in various ways. The availability of biomass limits the capacity of the plant [46]. The purchase price of biomass was found to be a significant cost component in [66,73,77,79]. The yield per hectare of biomass was also known as an influential factor in [69,76]. The biomass with higher yield per hectare

requires fewer truck movements to be collected from different collection areas, thus the transportation cost would be lower than that for biomass with lower yield per hectare. Also, the transportation cost is less for biomass with higher bulk density. This was covered in [77,48]. More wood can be transported within the same truck when bulk density is higher. Mitchell et al. [69] referred to moisture content as an important factor particularly for technologies that require very low moisture content, e.g. pyrolysis. Lower pretreatment cost would be a cost advantage in this case.

Procurement cost of biomass includes harvesting, collecting, transportation of biomass to forest road and finally to the plant. Since these activities can account for more than 50 percent of forest fuel supply [46], the related costs are very influential in economic viability of using forest biomass. The supply cost of forest biomass was referred to as an influential factor in [47,49]. Some studies focused exclusively on transportation costs. Caputo et al. [70] and Gautam et al. [51] highlighted the importance of transportation costs. The improvement in efficiency of collection technologies were recognized to be associated to lower costs of energy generation by Yoshioka et al. in [48].

Conversion technology can affect the feasibility of using forest biomass for district energy generation. The operating scale of energy plant is an important factor. Larger plants show cost advantage over smaller ones since the specific capital cost decreases as systems get larger. However, larger capacities do not necessarily guarantee less expensive energy generation. Large scaled plants need more biomass to be purchased and collected from farther distances, which impose higher transportation cost to the system. Furthermore, as it was discussed previously the capacity of biomass plant is limited to the amount of available biomass [70,78,67].

Efficiency of a conversion technology can influence the economic feasibility. The higher the efficiency is, the less the amount of purchased biomass would be. The less the amount of required biomass, the less the transportation cost would be. Varela et al. [71] discussed that using a more efficient technology could generate more electricity. However, Mitchell et al. [69] and Caputo et al. [70] showed that the cost savings due to higher efficiencies of these systems may not offset their higher capital cost.

Using novel technologies, mainly gasification and pyrolysis systems, was found to be less attractive in district energy plants. The drawbacks of these systems are high capital cost and high labor cost. Bridgwater et al. [72] and Yagi et al. [79] recognized that energy generation using novel technologies would cost too much, however they emphasized that learning and gaining experience would reduce the costs in the future.

Policies and government incentives have a key role in promoting and encouraging more investments in biomass district energy systems. Introducing CO_2 taxes and tradable carbon credits were regarded as policies that would encourage investments in biomass district energy systems in [66,76,75,50]. The experience in Australia in setting up tradable carbon credit can be used by other countries. Rodriguez et al. [77] showed that this policy in Australia has improved the energy generation using local biomass. However, policies that can enhance the share of biomass in energy generation are not limited to financial ones. Kinoshita et al. [50] referred to increasing the rotation period of trees as an important factor in making biomass profitable to be used in energy generation market in Japan. Schneider et al. [66] and Dwivedi et al. [78] argued that subsidies and grants would be essential to make biomass district energy systems of their studies profitable.

6. Conclusions and directions for future research

The reviewed literature in this paper indicates that despite the many advantages of forest biomass, costs associated with material collection, storage, transportation, and conversion exceed its value on district energy market. Fossil fuels appear to be still more attractive than forest biomass for district energy because of their lower price and their more cost-effective supply chain and logistics process.

Forest biomass for district energy holds a great potential to reduce greenhouse gas emissions. However, the realization of this potential is occurring slower than the expected pace today [80]. To accelerate the development of district heat and power generation from forest biomass, supportive policies and incentives are required to overcome the immaturity of the forest biomass value chain. Löfstedt [81] mentioned that government economic subsidies have been the most important factor in the success of Sweden to fulfill a major part of the heat demand using forest biomass in district energy systems. District energy providers should regard forest biomass as an investment with long term payback and wait for learning effects to decrease production costs. However, the increase in the demand for forest biomass can lead to unsustainable harvesting levels which have negative impacts on biodiversity, soil, and water conservation [82]. The sustainability of forest biomass harvesting can be ensured through setting new standards and legislations.

One way to increase district heat and power production from forest biomass is co-firing it with coal in existing coal energy plants. It is estimated that to burn biomass in coal power plants under European conditions, an investment in the range of 5–10 EUR per MWh is required to upgrade plant equipment including storage, grinders, feed systems, burners, air blowers, and flue gas cleaning equipment [80].

Recently, the environmental advantages of these systems have become the encouraging factor for establishing these energy plants. To take advantage of benefits of district energy systems, incentives from governments are essential. The impact of using more efficient technology particularly in handling and transporting biomass has not been investigated, yet. Also, further research is needed on the performance of biomass district energy systems considering their environmental and social impacts in addition to their costs.

References

[1] Levine M, Ürge-Vorsatz D, Blok K, Geng L, Harvey D, Lang S, et al. Residential and commercial buildings. Clim Change 2007:387–446.
[2] Levermore G. A review of the IPCC assessment report four, part 1: the IPCC process and greenhouse gas emission trends from buildings worldwide. Build Serv Eng Res Technol 2008;29:349–61.
[3] Blok K. Enhanced policies for the improvement of electricity efficiencies. Energy Policy 2005;33:1635–41.
[4] Lund H. Implementation of energy-conservation policies: the case of electric heating conversion in Denmark. Appl Energy 1999;64:117–27.
[5] Li DHW, Yang L, Lam JC. Zero energy buildings and sustainable development implications – a review. Energy 2013;54:1–10.
[6] Afgan NH, Carvalho MG. Sustainability assessment of hydrogen energy systems. Int J Hydrog Energy 2004;29:1327–42.
[7] Lior N. Thoughts about future power generation systems and the role of exergy analysis in their development. Energy Convers Manag 2002;43:1187–1198.
[8] Esen M, Yuksel T. Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy Build 2013;65:340–51.
[9] Chau J, Sowlati T, Sokhansanj S, Preto F, Melin S, Bi X. Techno-economic analysis of wood biomass boilers for the greenhouse industry. Appl Energy 2009;86:364–71.
[10] Esen H, Inalli M, Esen M. Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey. Energy Convers Manag 2006;47:1281–97.
[11] Esen H, Inalli M, Esen M. A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling. Build Environ 2007;42:1955–65.
[12] Ghafghazi S, Sowlati T, Sokhansanj S, Melin S. Techno-economic analysis of renewable energy source options for a district heating project. Int J Energy Res 2010;34:1109–20.
[13] Ghafghazi S, Sowlati T, Sokhansanj S, Melin S. A multicriteria approach to evaluate district heating system options. Appl Energy 2010;87:1134–40.
[14] Dincer I, Rosen MA. Exergy: energy, environment and sustainable development. 2nd ed.. Newnes: Elsevier; 2012.

[15] Gilmour B, Warren J. Advancing district energy development in Canada: a process for site selection, review and community participation. Toronto, ON: Canadian District Energy Association; 2007.
[16] Gustavsson L, Karlsson Å. Heating detached houses in urban areas. Energy 2003;28:851–75.
[17] Difs K, Danestig M, Trygg L. Increased use of district heating in industrial processes – impacts on heat load duration. Appl Energy 2009;86:2327–34.
[18] Rezaie B, Rosen MA. District heating and cooling: review of technology and potential enhancements. Appl Energy 2012;93:2–10.
[19] Rosen MA, Le MN, Dincer I. Efficiency analysis of a cogeneration and district energy system. Appl Therm Eng 2005;25:147–59.
[20] Solomon B, Luzadis VA. Renewable energy from forest resources in the United States. US: Taylor & Francis; 2008.
[21] Hall D, Scrase J. Will biomass be the environmentally friendly fuel of the future? Biomass Bioenergy 1998;15:357–67.
[22] Ayhan D. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Convers Manag 2001;42:1357–78.
[23] Openshaw K. Biomass energy: employment generation and its contribution to poverty alleviation. Biomass Bioenergy 2010;34:365–78.
[24] McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresour Technol 2002;83:37–46.
[25] Castellano PJ, Volk TA, Herrington LP. Estimates of technically available woody biomass feedstock from natural forests and willow biomass crops for two locations in New York State. Biomass Bioenergy 2009;33:393–406.
[26] Skoulou V, Zabaniotou A. Investigation of agricultural and animal wastes in Greece and their allocation to potential application for energy production. Renew Sustain Energy Rev 2007;11:1698–719.
[27] Gan J. Supply of biomass, bioenergy, and carbon mitigation: method and application. Energy Policy 2007;35:6003–9.
[28] Madlener R, Bachhiesl M. Socio-economic drivers of large urban biomass cogeneration: sustainable energy supply for Austria's capital Vienna. Energy Policy 2007;35:1075–87.
[29] Sokhansanj S, Turhollow A. Biomass densification-cubing operations and costs for corn stover. Appl Eng Agric 2004;20:495–502.
[30] Rentizelas AA, Tolis AJ, Tatsiopoulos IP. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew Sustain Energy Rev 2009;13:887–94.
[31] Jones G, Loeffler D, Butler E, Hummel S, Chung W. The financial feasibility of delivering forest treatment residues to bioenergy facilities over a range of diesel fuel and delivered biomass prices. Biomass Bioenergy 2013;48:171–80.
[32] Sacchelli S, De Meo I, Paletto A. Bioenergy production and forest multifunctionality: a trade-off analysis using multiscale GIS model in a case study in Italy. Appl Energy 2013;104:10–20.
[33] Scarlat N, Blujdea V, Dallemand J. Assessment of the availability of agricultural and forest residues for bioenergy production in Romania. Biomass Bioenergy 2011;35:1995–2005.
[34] Schmidt J, Leduc S, Dotzauer E, Kindermann G, Schmid E. Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. Int J Energy Res 2010;34:970–85.
[35] Angelis-Dimakis A, Biberacher M, Dominguez J, Fiorese G, Gadocha S, Gnansounou E, et al. Methods and tools to evaluate the availability of renewable energy sources. Renew Sustain Energy Rev 2011;15:1182–200.
[36] MacFarlane DW. Potential availability of urban wood biomass in Michigan: Implications for energy production, carbon sequestration and sustainable forest management in the USA. Biomass Bioenergy 2009;33:628–34.
[37] López-Rodríguez F, Atanet CP, Blázquez FC, Celma AR. Spatial assessment of the bioenergy potential of forest residues in the western province of Spain, Caceres. Biomass Bioenergy 2009;33:1358–66.
[38] Vasco H, Costa M. Quantification and use of forest biomass residues in Maputo province, Mozambique. Biomass Bioenergy 2009;33:1221–8.
[39] Viana H, Cohen WB, Lopes D, Aranha J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Appl Energy 2010;87:2551–60.
[40] FAO. Estimating biomass and biomass change of tropical forests: a primer. Food and Agricultural Organization of United Nations; 1997.
[41] Brown SL, Schroeder P, Kern JS. Spatial distribution of biomass in forests of the eastern USA. For Ecol Manag 1999;123:81–90.
[42] Paré D, Bernier P, Thiffault E, Titus BD. The potential of forest biomass as an energy supply for Canada. For Chron 2011;87:71–6.
[43] Fischer G, Prieler S, van Velthuizen H. Biomass potentials of miscanthus, willow and poplar: results and policy implications for Eastern Europe, Northern and Central Asia. Biomass Bioenergy 2005;28:119–32.
[44] Smeets EM, Faaij AP. Bioenergy potentials from forestry in 2050. Clim Change 2007;81:353–90.
[45] Becker DR, Klapperich JJ, Domke GM, Kilgore MA, D'Amato AW, Current DA, et al. Outlook for forest biomass availability in Minnesota: physical, environmental, economic, and social availability. College of Food, Agricultural and Natural Resource Sciences. St. Paul, Minnesota: University of Minnesota; 2010.
[46] Allen J, Browne M, Hunter A, Boyd J, Palmer H. Logistics management and costs of biomass fuel supply. Int J Phys Distrib Logist Manag 1998;28:463–77.
[47] Ćosić B, Stanić Z, Duić N. Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: case study Croatia. Energy 2011;36:2017–28.
[48] Yoshioka T, Sakurai R, Aruga K, Sakai H, Kobayashi H, Inoue KA. GIS-based analysis on the relationship between the annual available amount and the procurement cost of forest biomass in a mountainous region in Japan. Biomass Bioenergy 2011;35:4530–7.
[49] Ahtikoski A, Heikkilä J, Alenius V, Siren M. Economic viability of utilizing biomass energy from young stands – the case of Finland. Biomass Bioenergy 2008;32:988–96.
[50] Kinoshita T, Ohki T, Yamagata Y. Woody biomass supply potential for thermal power plants in Japan. Appl Energy 2010;87:2923–7.
[51] Gautam S, Pulkki R, Shahi C, Leitch M. Economic and energy efficiency of salvaging biomass from wildfire burnt areas for bioenergy production in northwestern Ontario: a case study. Biomass Bioenergy 2010;34:1562–72.
[52] Akhtari S. Economic assessment and optimization of forest biomass supply chain for heat generation in a district heating system. Vancouver, British Columbia: University of British Columbia; 2012.
[53] Tahvanainen T, Anttila P. Supply chain cost analysis of long-distance transportation of energy wood in Finland. Biomass Bioenergy 2011;35:3360–75.
[54] Kinoshita T, Inoue K, Iwao K, Kagemoto H, Yamagata Y. A spatial evaluation of forest biomass usage using GIS. Appl Energy 2009;86:1–8.
[55] Mahmoudi M, Sowlati T, Sokhansanj S. Logistics of supplying biomass from a mountain pine beetle-infested forest to a power plant in British Columbia. Scand J For Res 2009;24:76–86.
[56] Mobini M, Sowlati T, Sokhansanj S. Forest biomass supply logistics for a power plant using the discrete-event simulation approach. Appl Energy 2011;88:1241–50.
[57] EPA. Biomass conversion: emerging technologies, feedstock and products. Washington, DC: United States Environmental Protection Agency; 2007.
[58] Quaak P, Knoef H, Stassen HE. Energy from biomass: a review of combustion and gasification technologies. World Bank-free PDF, vol. 23; 1999. p. 78.
[59] McKendry P. Energy production from biomass (part 2): conversion technologies. Bioresour Technol 2002;83:47–54.
[60] Knoef H. Fixed bed gasification. . Enscheda, Netherlands: IEA Task; 2003.
[61] Bridgwater T. Biomass pyrolysis. UK: Aston University; 2007.
[62] Sjaak VL, Koppejan J. The handbook of biomass combustion and co-firing. London, UK: EarthScan; 2007.
[63] Preto F. Review of biomass conversion technologies. In: Proceedings of the bioenergy solutions for community sustainability workshop. Prince George, BC, Canada; 2010.
[64] Baxter D, Scarlat N, Giuntoli J. Bioenergy – power and heat generation – 2011 update of the technology map for the SET-Plan; 2011.
[65] UNF. Sustainable bioenergy development in UEMOA member countries. United Nations Foundation. Geneva, Switzerland: International Centre for Trade and Sustainable Development (ICTSD); 2008.
[66] Schneider B, Kaltschmitt M. Heat supply from woody biomass – an economic analysis. Ecol Eng 2000;16:123–35.
[67] Fischer B, Pigneri A. Potential for electrification from biomass gasification in Vanuatu. Energy 2011;36:1640–51.
[68] Heat C. Biomass combined heat and power: catalog of technologies. Washington, DC: US Environmental Protection Agency, Combined Heat and Power Partnership; 2007.
[69] Mitchell C, Bridgwater A, Stevens D, Toft A, Watters M. Technoeconomic assessment of biomass to energy. Biomass Bioenergy 1995;9:205–26.
[70] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass Bioenergy 2005;28:35–51.
[71] Varela M, Sáez R, Audus H. Large-scale economic integration of electricity from short-rotation woody crops. Sol Energy 2001;70:95–107.
[72] Bridgwater A, Toft A, Brammer J. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renew Sustain Energy Rev 2002;6:181–246.
[73 Nicholls DL, Crimp PM. Feasibility of using wood wastes to meet local heating requirements of communities in the Kenai Peninsula in Alaska. United States Department of Agriculture Forest Service General Technical Report Pnw; 2002.
[74] Broek R, Teeuwisse S, Healion K, Kent T, van Wijk A, Faaij A, et al. Potentials for electricity production from wood in Ireland. Energy 2001;26:991–1013.
[75] Gan J, Smith CT. A comparative analysis of woody biomass and coal for electricity generation under various CO_2 emission reductions and taxes. Biomass Bioenergy 2006;30:296–303.
[76] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass Bioenergy 2003;24:445–64.
[77] Rodriguez LC, May B, Herr A, O'Connell D. Biomass assessment and small scale biomass fired electricity generation in the Green Triangle, Australia. Biomass Bioenergy 2011;35:2589–99.
[78] Dwivedi P, Alavalapati JRR. Economic feasibility of electricity production from energy plantations present on community-managed forestlands in Madhya Pradesh. India Energy Policy 2009;37:352–60.
[79] Yagi K, Nakata T. Economic analysis on small-scale forest biomass gasification considering geographical resources distribution and technical characteristics. Biomass Bioenergy 2011;35:2883–92.
[80] European Climate Foundation. Biomass for heat and power – opportunity and economics; 2010.
[81] Löfstedt RE. The use of biomass energy in a regional context: the case of Växjö Energi, Sweden. Biomass Bioenergy 1996;11:33–42.
[82] Caputo J. Sustainable forest biomass: promoting renewable energy and forest stewardship. Washington, DC: The Environmental and Energy Study Institute (EESI); 2009.
[83] Fare R, Grosskopf S, Kokkelenberg EC. Measuring plant capacity, utilization and technical change: a nonparametric approach. Int Econ Rev 1989:655–66.